LCA application in the fruit sector: State of the art and recommendations for environmental declarations of fruit products

Published version:

DOI:10.1016/j.jclepro.2013.09.017

LCA application in the fruit sector: State-of-the-art and recommendations for environmental declarations of fruit products

Alessandro K. Cerutti[1,5], Gabriele L. Beccaro[1], Sander Bruun[4], Simona Bosco[2,5], Dario Donno[1], Bruno Notarnicola[3,5], Giancarlo Bounous[1]

[1] Department of Agriculture, Forestry and Food Science, University of Torino, Via Leonardo da Vinci, 44 – 10095 Grugliasco (TO), Italy
[2] Institute of Life Sciences – Scuola Superiore S. Anna, Piazza Martiri della Libertà, 33 - 56127 Pisa, Italy
[3] Ionian Department, University of Bari Aldo Moro, via Lago Maggiore angolo via Ancona, 74121 Taranto, Italy.
[4] Department of Agriculture and Ecology, Faculty of Life Sciences, University of Copenhagen, Denmark
[5] Italian LCA Network
[*] Corresponding author. E-mail: *alessandrokim.cerutti@gmail.com*

ABSTRACT

Modern food production is very diverse, with high levels of specialization and complexity. These features inevitably reflect on methods for the application of LCA to food products and agro-systems. Several aspects, including system boundaries, functional units and allocation procedures contribute to deeply differentiate the structure of LCA application in fruit production systems, leading to significantly different results. Indeed, even if the scientific literature on the topic is recent and not very large, several different ways of conducting LCAs in orchards can be found.
The aim of the paper is to propose a framework for choosing the best settings for an LCA application in fruit production systems according to the object of the study. This result was achieved by reviewing the scientific and technical literature on the topic. In particular, papers from international journals and conference proceedings were considered and the review covers all main aspects for conducting an LCA in fruit production systems. Particular characteristics considered were objectives, system boundaries, product considered, functional unit, data origin and the environmental impact assessment method used.
A relevant part of the paper is devoted to the modelling of the orchard, as this is a keystone for a reliable application of any impact assessment approach. More than a description of the theoretical model, the paper presents concrete recommendations about how to build an orchard system for LCA application avoiding over- or under-estimations of the different orchard stages.

Keywords: fruit products, orchard, sustainable production, system boundaries, functional unit, system modelling for impact assessment

1 Introduction

In 2010, world production of fruit was 609,213,512 t, mostly concentrated in Asia (52%) and America (22%) (FAOSTAT, 2012). In Europe, 67,254,709 t of fruit were produced, corresponding to about 11% of the fruit produced in the world, with significant contributions by Italy (25.14% of the fruit produced in Europe), Spain (22.57%) and France (12.93%). The important role played by the Asian markets is even more evident upon analysing production trends in the past 10 years: while America, Europe, Africa and Oceania have a fairly constant fruit production, in Asia it has increased by about 55%, making China and India the highest producers of fruit in the world, with 20.06% and 13.92% of world production, respectively.

Fruit products are generally considered to have less potential environmental impact than most foods in occidental diets. For example, Carlsson-Kanyama et al. (2003) quantified the energy consumption of different diets and reported an average of 5 MJ per kg of in-season fruit (26 MJ per kg of out-of-season fruit), 15 MJ per kg of vegetables, 17 MJ per kg of bread and flour products, 33 MJ per kg of dairy products, 37 MJ per kg of meat, and 75 MJ per kg of fish products. On the other hand, compared to other food products, fruit production is considered an intensive agricultural system in terms of inputs of pesticides and fertilizer as well as investments in capital and material (e.g. Mouron et al., 2006a). Indeed the embodied energy of orchard infrastructures, such as hail nets and irrigation pipes, is higher than in other cropping systems.

Furthermore, studies examining the carbon footprint of different food choices have reported that fruit is the food category with the least potential environmental impact (e.g. Wallén et al., 2004; Berners-Lee et al., 2012). However, these studies use data from environmental assessments of generic fruit production, which don't take into account specific issues within orchard systems and fruit supply chains. Indeed, different results may arise considering the production system (e.g. conventional or organic), the production site (specific soil and climate conditions affecting yield and agronomic performance) or the retailing system (long-term cold storage may dramatically influence the environmental performance of the product). Recently Mouron et al., (2012) demonstrated that the same apple cultivation in five European regions may have completely different protection requirements leading to very different environmental impacts.

High levels of specialisation, diversification and complexity in orchard systems inevitably reflect on methods for the application of LCA to food products and agro-ecosystems (Notarnicola et al., 2012a). It is therefore important to study the work that has already been done regarding standardisation of methods in order to make appropriate comparisons between products.

The main aim of the paper is to describe a reference framework for choosing the best settings for LCA applications in fruit production systems. In order to achieve this goal, recommendations were collected and discussed through reviewing studies assessing LCA application in fruit production systems in the scientific and technical literature. Furthermore, secondary goals of the papers are: (ii) identifying aspects of fruit production that are of environmental importance according to the studies reviewed, (iii) discuss harmonization projects, (iv) give practical recommendations about how to model orchards for LCA applications. Therefore, section 2 describes what is the state-of-the-art about LCA in fruit production according to a literature review procedure described in 2.1. In this section both general and critical aspects are highlighted, such as the choice of functional unit and the ways of modelling the orchard. Section 3 moves from academic studies to environmental product declarations and harmonization initiatives as important sources for highlighting practices in LCA application in the sector. In Section 4 recommendations and best practices are presented; in particular, section 4.1 deals with a concrete description of orchard modelling and 4.2 focuses on all the other LCA settings for achieving the most reliable results according to the aim of the application.

2 State-of-the-art of LCA applied to fruit production

2.1. Academic literature review method

In the present review of LCA application in fruit systems, only peer-reviewed papers from international journals and conference proceedings were considered. Studies that included the fruit production stage were preferentially selected, while studies that considered the whole production of derivatives (e.g. fruit juice) were only included if they added to the analysis of the growth stage. The review covered all main aspects for conducting an LCA in fruit production systems. Particular characteristics considered were objectives, system boundaries, product considered, functional unit, data origin and environmental impact assessment method used.

After a preliminary study of the literature on LCA applications in the food sector, nine objectives were found to be the most common goals of LCAs in the fruit sector. These objectives were to: 1) profile the environmental burden of a fruit product, in which a specific production system is evaluated and results are related to the case study without any intent to generalise; 2) identify the environmental hotspots in production system performance considering the different field operations and stages of the system; 3) describe management strategies to improve environmental performance, a focus usually applied after objective 2 in order to give practical suggestions after the evaluations; 4) compare the environmental burdens of different food products on a common functional unit, e.g. a specific unit of nutrient content; 5) compare different farming practices, e.g. organic and conventional; 6) compare different environmental assessment methods, such as LCA, ecological footprint analysis and water footprint, in the same case study; 7) profile the environmental burden of production in a given area, by applying the LCA evaluation to a statistical database on farms in that specific area; 8) evaluate the environmental properties of a supply chain, usually with the focus on differences in environmental impact for long and short distances between production and consumption sites; and 9) assess a preliminary study for statistical investigations. In this case the LCA results were used with the results of other indicators to elaborate complex indices.

2.2. General aspects

A total of 19 studies were identified; 11 articles in ISI journals and eight papers in proceedings from the LCA congress series (Table 1).

→ **Table 1**. List of all papers from ISI journals and conferences that present applications of LCA in fruit production systems up to January 2013, listed by ascending date of publication. Country category considers the area of the study and not necessarily the location of the research group. Objectives: 1) profile the environmental burden of a fruit product; 2) identify the environmental hotspots in production system performance; 3) describe management strategies to increase environmental performance; 4) compare the environmental burdens of different food products on a common functional unit; 5) compare different farming practices; 6) compare different environmental assessment methods; 7) profile the environmental burden of production in a given area; 8) evaluate the environmental properties of a supply chain; and 9) assess a preliminary study for statistical investigations.

General aspects of the cases studied. With the exception of rare pioneer studies, it can be assumed that mainstream research on LCA applied to fruit production systems began around 2005. A number of papers were published in 2010 in conjunction with the 7th International Conference on LCA in the Agri-Food Sector, following the increasing trend of participation in congresses relating to LCA of food (Notarnicola, 2012b). Despite the high quantity of fruit produced in Asia, most of the LCA applications published internationally focused on case studies located in Europe and South America and just one study focused on China (Liu et al., 2010). It is therefore realistic to assume that in the coming years much research on this subject will focus on the Asian continent, both for case studies and for environmental evaluation of fruit commercialisation.

Objectives. Most papers in the literature state more than one objective, with the exception of studies on the supply chain (objective 8), which usually focus on just this aspect (e.g. Blancke and Burdick, 2005), even if they also investigate the field phase of the production process (e.g. Knudsen et al., 2011). Description of the environmental burden of the product (objective 1) is the first objective of all studies, but it is often not the main objective, which instead may be a comparison of different methods, for example (e.g. Cerutti et al., 2010). Suggestions on ways to move towards sustainability (objective 3) are often associated with the evaluation of environmental hotspots (e.g. Cudjoe et al., 2010). The comparison of different methods is not

usually applied to fruit production; it can be found only in one comparison each of LCA with Ecological Footprint Analysis (Cerutti et al., 2010) and LCA with PAS 2050 (McLaren et al., 2010).
Data origin. Most of the studies reviewed (11 papers) were based on data collected from commercial orchards, either directly in field surveys or via questionnaires or interviews with farmers. Sometimes these approaches are mixed and the data collection method used for the different data in the study is not always clearly described. Four studies investigated commercial orchards and then compared the field dataset obtained with reference values. This approach allows conclusions to be drawn about specific orchards, while the validation for identifying unusual agricultural practices only of interest for the specific farm (e.g. Milà i Canals et al., 2006). The other method used to obtain statistically robust datasets is to include a large number of commercial orchards and consider average values for these farms. Furthermore, data from statistically robust datasets can also be used to provide information about the distribution of the data, such as standard deviation and skewness (Mouron et al., 2006b). Seven studies used literature and available databases in order to obtain data instead of surveying commercial orchards. By applying this approach it is possible to obtain more generic results, but it is impossible to consider site-specific differences between orchards.
Environmental impact assessment method. Using different environmental impact assessment methods may lead to different conclusions. Across the 19 papers reviewed, the typical impact categories used are those which quantify effects on ecosystems other than those on resource consumption or human toxicity, with particular attention to the potential for global warming, eutrophication and acidification. Global warming potential is mainly related to the combustion of fuels and thus is considered a key indicator in studies involving comparisons of systems with different transport distances (e.g. Blanke and Burdick, 2005; Cerutti et al., 2011). Eutrophication and acidification are generally more related to the use of fertilisers and pesticides (Hauschild, 2000) and thus depend on the farming practices used and climate conditions.
When defining the impact categories for fruit production, it is very important to consider the typical environmental problems that may arise in orchards (Milà i Canals et al., 2006). Fruit is usually produced in temperate sunny regions because sun increases yield and improves fruit quality. However, these regions are also prone to water scarcity and losses of nutrients and pesticides to the surrounding environment. These effects can influence all impact categories, but particularly nutrient enrichment potential and acidification potential (Coltro et al., 2009) as well as human toxicity.

2.3. Modelling orchard systems

Building a good model of the system that can correctly describe the real system is of the utmost importance (e.g. Mouron et al. 2012). In this regard, precise definition of system boundaries is essential.
In the reviewed literature, the two most frequently used system boundaries were cradle-to-gate and cradle-to-market. In the cradle-to-gate category, the environmental impacts were quantified for the production phase including all upstream impacts until the farm gate (8 papers). The cradle-to-market category includes studies in which the distribution and commercialisation phase was included in the assessment (9 papers). Two particular boundaries are cradle-to-retailer (2 papers), in which processing and transport to the distribution system are also accounted for, and cradle-to-use (1 paper), in which impacts from the consumer phase are also accounted for. The nursery where orchard seedlings are produced should be considered an upstream process delivering grafted plants to the orchards and the impact during this stage should be included in assessments of fruit production systems even if those impacts are spread during the lifetime of the orchard (see section 2.4). However, although many authors stress that it is important to consider the nursery in environmental impact assessments (Milà i Canals and Polo, 2006; Cerutti et al., 2010), the lack of data makes this difficult.

For the purposes of efficient modelling of an orchard system, it is necessary to take into account two aspects:
(I) Orchards are biological systems. As for all other food production systems, the variability and unpredictability of living systems must be taken into account. Unlike industrial production, where the amount of commercial product is known and given as a reliable function of the inputs supplied, biological systems can have variable yields depending on environmental conditions (biotic and abiotic). The strong

dependence of biological production systems on weather conditions is also expressed as variations in the quantity of agricultural inputs needed to maintain production at the desired level. For example, in years with very high spring temperatures the risk of pest attacks increases dramatically, with a consequent increase in agrochemical use (Sansavini et al., 2012) that affects both their impact on production and on input losses (leaching for instance).

(II) Orchards are perennial systems. Unlike field crops, the life cycle of which is completed in less than a year, fruit systems involve plants with very variable duration (10–30 years) depending on the crop and management practice. The long cropping cycle of orchards means that there are processes that occur once in the entire life cycle (e.g. during orchard establishment and disposal) and other processes that are repeated a number of times depending on the length of the cycle (e.g. pruning and fertilisation). Furthermore, most temperate fruit cultures reach maturity in 2–4 years after establishment of the orchard. Before that age, the yield may be significantly lower (or even zero) because the plants are still too young. This may significantly affect the average yield and has to be considered. Furthermore, the yield variability between years may be very high. For example, McLaren et al. (2010) reported that the highest yield for green kiwifruit over a period of six years was 31% greater than the lowest.

These two characteristics add complexity to modelling fruit systems, but if the productive period is considered exclusively then the environmental impacts of the final product are considerably underestimated (Cerutti et al., 2010, 2011).

A detailed model of a fruit production system may take these two aspects into account by dividing the system into different stages (Figure 1). This modelling approach was originally proposed by (Mila i Canals et al., 2006) and later validated (Cerutti et al., 2010; Cerutti et al., 2011); in particular, six main stages have been considered: (1) Nursery phase for producing rootstocks, scions and whips ready to plant, (2) planting and field preparation for the orchard, (3) early low production phase due to the immaturity of the system, (4) full production, (5) low production phase due to plant senescence and (6) removal and disposal of plants. It has to be noted that the latter two stages are theoretical and they are rarely found in commercial orchards in Europe since fruit growers replace the orchards at the end of stage 4 for economic reasons.

→ **Figure 1**: Graphic representation of real and average production per stage throughout the entire life of an apple orchard in Cuneo province, northern Italy, divided into six stages of production (modified from Cerutti et al., 2011).

Considering this model, stages 1, 2 and 6 do not have output in commercial production, but may contribute to the generation of environmental impacts of the product. Stages 3, 4 and 5 are those in which fruit is produced and the annual quantity of output may be variable from year to year. Although it is very difficult to find data for production as a function of orchard age, it is recommended that average production data (measured or modelled) be used for each of stages 3–5 (Figure 1).

2.4. The nursery subsystem

In the reviewed literature, minor importance is given to the nursery. Just three studies assessed the environmental impacts of the nursery as a stage of the whole production system. Although in some perennial plantation systems its relative contribution may be negligible (Yusoff and Hansen, 2007), the nursery stage may play an important role for plants that need special protection in the early stages, such as specific growth substrates (Ingram, 2012) or plastics for greenhouses (Russo and Scarascia Mugnozza, 2005).

Because of all the nursery-related impacts, the application of an environmental indicator just to the full production year will probably underestimate the real environmental impact by a variable percentage (about 30% in the studies reviewed here, depending on the fruit considered and assessment method) (Figure 3).

→ **Figure 2.** Hotspot analysis of two previous case studies. Modified from Cerutti et al., 2011.

As the environmental impacts of the nursery stage are allocated per plant grafted or planted in the orchard, there is a strong relationship between the density of the plantation and the relative impact of the nursery

(Cerutti et al., 2013). Although this relationship can be easily observed in comparative studies, because of the small number of LCA studies on fruit that include the nursery stage, no significant correlation with the fruit species or the proportion of total impacts can be identified so far.
Therefore, adopting a fraction of field production impacts considering the theoretical duration and plant capacity of the nursery study as a proxy is a risky approach that should be avoided when reliable data or reference case studies are available. The only way of covering the lack of knowledge is to increase the number of studies including the nursery stage and include nursery average impacts in LCA databases and tools, as is already done for other inputs such as fertilisers and pesticides.

2.5. Which functional unit to use?

The functional unit helps quantify the productive output of the orchard in order to make different production systems comparable. Fruits and fruit products may have different quality, nutrient and economic values, and thus it may be difficult to find a useful functional unit. In most cases, however, the definition of a functional unit (e.g. 1 kg of product) is made without much discussion. Several different units were used in the 19 papers reviewed here and these can be categorised into three different types:

(i) Mass-based functional units, where the environmental impacts are related to a specific amount of product produced. In total, there were 18 applications of this type of functional unit in the papers reviewed here. Environmental impacts are usually related to the production of one metric tonne of fruit if the system boundaries focus on the farm gate, or the production of one kilogram of fruit if a cradle-to-table approach is used. When using a mass-based functional unit, problems may arise in how to account for fruit quality (Mila i Canals et al., 2006). The same orchard can usually produce fruit of different quality (e.g. size, colour, firmness or sugar content) that is targeted to different markets (e.g. fresh market or industrial processing). Although the chemical and fiscal properties of fruit are not sufficient to define quality, the functional unit can be defined to include the obligatory product properties required by the market segment (Peacock et al., 2011)
Looking only at environmental impacts per unit mass of product evaluates the eco-efficiency of the production but not its sustainability, because efficiency does not necessarily lead to sustainability (Wackernagel and Rees, 1997; van der Werf et al., 2007). Furthermore, the same increase in efficiency that contributes to a higher income can be negatively correlated with environmental impacts (Mouron et al., 2013).

(II) Land use-based functional units, where the environmental impacts are related to the management of one hectare of orchard. A land-based and a currency-based functional unit is used in just one of the studies reviewed (Mouron et al., 2006b). A land use-based functional unit, such as 1 ha of orchard, is not frequently used in LCA, partly because land use is not a service and does not provide a productive function, even if land that is suitable for fruit production is often rare. In fact, it makes more sense to consider land use an environmental impact in an LCA. However, land use is an integrated line of thinking in an agronomic setting and can give interesting results. In general, converting resource consumption or environmental impacts to units of land use allows evaluation of the impacts of cultivating a certain area. This parameter is also called the impact intensity of a farm (Mouron et al., 2006b). The land use-based functional unit in fruit production is complementary to the mass-based functional unit because they give different results and both should be used. Indeed, when considering just impacts per unit area, low input-output systems will have a better ranking for decreased impacts at the regional level. From a life cycle perspective, however, they create a need for additional land use to produce a similar amount of product as high input-output systems, giving rise to additional impacts (van der Werf et al., 2007).
Furthermore, the use of a mass-based or a land-based functional unit reflects the perspective addressed by the particular study: the former is used in product-orientated expression of agricultural production and the latter in land-orientated expression (Hayashi, 2013). Furthermore, a land-based functional unit represents the land management function of agriculture (Nemecek et al., 2011).

(III) Economic value-based functional units, where the environmental impacts are related to a particular amount (€) of grower income from wholesale fruit sales. It is used in just one application in the papers reviewed here. This functional unit is useful because it integrates product quantity and quality in a single measure (Mouron et al., 2006b), but it is strongly influenced by the economic context in which the farm is located and can change significantly from one year to another. Therefore, the reference period should be several years. In Mouron et al. (2006b) 4 years were taken into account, because of the property of the specific fruit produced to alternate high production and low production years (biennial bearing).

A recent study (Cerutti et al., 2013) points out that comparing the same fruit production systems with different functional units may lead to completely different scenarios. In particular, fruit cultivars with a higher yield show significantly better environmental performance using a mass-based functional unit, while fruit cultivars with lower yield are favoured by a land use-based functional unit (Cerutti et al., 2013). That study also showed that different functional units used in LCA actually address different research questions, so the scope of the research has to be carefully described.

Another important aspect in the study of the most suitable functional unit for fruit production is the problem of food waste. Indeed, as most fruit is rapidly perishable, quantification of product loss in the supply chain is needed in order to evaluate the environmental impact of the product actually consumed (Ingwersen, 2010). This aspect is crucial for assessments that include the market or the consumer phase in their boundaries. Indeed for a specified unit of product sold or consumed there is a specific amount (or an average range of amount) that is wasted. Nevertheless, in a strictly productive framework, i.e. when a cradle-to-gate assessment was adopted, the aspect of food waste was not addressed among the considered papers.

3. LCA of fruit product in technical reports and international initiatives

3.1 Environmental declarations of fresh fruit and fruit products

Nowadays LCA approaches are considered the basis for communicating the overall environmental performance of products (Ingwersen and Stevenson, 2012) and several frameworks for Environmental Product Declarations (EPDs) are available. One of the most widely used declaration systems to include LCA of food products is the international EPD® System, standardised as type III labelling (ISO 14025). This declaration system works with rules based on a hierarchic approach following the international standards ISO 9001, ISO 14001, ISO 14040, ISO 14044 and ISO 21930. As a consequence, the LCA approach is a mandatory procedure to be adopted and reference is made to LCA-based information as content to be considered in the product category rules (PCRs). According to the definition (Del Borghi, 2013), PCR documents define the requirements for EPDs in a certain product category and they enable transparency and comparability between different EPDs based on the same PCR. In fact these requirements are developed in collaborative frameworks with industries, research institutes and universities in order to achieve the best comparability of results between different producers of the same product.

Another important international framework for EPDs is the Product Environmental Footprint (PEF), which is a Life Cycle Assessment (LCA) based method to calculate the environmental performance of a product. It was developed by the European Commission's Joint Research Centre based on existing, extensively tested and used methods (European Commission, 2013). In this framework Product Environmental Footprint Category Rules (PEFCRs) are used but, up to now, the protocol is in the testing phase and no PEFCRs for fruit are available yet.

In the International EPD® system, fruit products are covered by a general PCR (Fruits and nuts - 2012:07) for the sector and five other specific PCRs (see Table 2 for details). These documents attempt to merge theoretical aspects for a scientifically sound assessment of the impacts and practical aspects in collecting data and managing the assessment. Indeed, the amount of work required to collect high-quality data has been recognised as a major obstacle for PCR production by small and medium-sized businesses (SMEs) (Zackrisson et al., 2008).

→ **Table 2.** Description of all the PCRs (and relative EPDs) which consider fruit products, both fresh and processed, registered in the International EPD® system.

In the general PCR for fresh fruits, it is recognised that standard sampling is quite unlikely to render a representative yield in kg of product per hectare or the yield factor per square metre of cropland required to produce 1 kg of product (Fruits and nuts - 2012:07 p. 10, section 7.4). Therefore three options are given: (a) adopting a typical yield factor (m^2/kg) previously agreed to between the interested parties in the area under evaluation, based on agronomic parameters and historical data for the area; (b) sample inflows/outflows from orchards of the same fruit in a group of farms to obtain an average yield factor; or (c) consider every production period as a unique batch in EPD terms, in which case the period of validity of the EPD will cover only a single production period.
Regarding the choice of functional unit, no specific suggestion can be found in the general PCR, but there is a recommendation to avoid allocating between grades of a product. In particular, it is stated that where fruits and nuts are destined for human consumption, even though they may be of potentially different grades, they are considered equivalent in terms of the service they deliver so no allocation is appropriate (Fruits and nuts - 2012:07 p. 9, section 7.3.1). Nevertheless, diversification of the supply for different grades of product from the same orchard is a very frequent procedure, with grade one fruits usually destined for the fresh market and other grades for industrial processing. Therefore, considering impacts from the mass of fruit that reaches the farm gate when considering a cradle-to-consumer approach may lead to misleading results.

3.2 Harmonization projects in LCA of fruit production

So far, different approaches and guidelines have been developed for harmonizing methods in calculating the environmental impact of food production systems. In particular, many guidelines have been elaborated with special focus on the GHG life cycle of goods and services, in the form of the Publicly Available Specification (PAS2050), developed by the British Standard Institute and the Carbon Trust (BSI, 2011; Carbon Trust, 2007), the French Bilan Carbone (ADEME, 2010), the GHG Protocol drawn up by the World Resources Institute and the World Business Council for Sustainable Development (WBCSD/WRI, 2009). Two specific ISO standards are under preparation on products' Carbon footprint, ISO 14067 (ISO, 2013a) and Water footprint (ISO, 2013b). What characterizes most these initiatives is the use of just a single indicator (carbon or water). On the other hand, the European Commission's Joint Research Centre is developing the Environmental Footprint for products, a harmonized framework to assess the sustainability of products, expected to be in line with ISO standards on life cycle assessment and with recognized scientific methodologies. Given the proliferation of standards and technical guides in the food and drink sector, a special focus has devolved to this sector with the creation in 2009 of the European Food Sustainable Consumption and Production Round Table. In this broad framework the main stakeholders from food industries are also partners, in order to promote a science-based, coherent approach to sustainable consumption and production in the European food sector across the whole life-cycle (Peacock et al., 2011). The first attempt at a harmonized method for the environmental assessment of food and drink products is the European Food SCP Roundtable's Draft Envifood Protocol issued in 2013 (European Commission, 2012), which, at the moment is in the testing phase. The main objective area is to provide guidance for assessments instrumental to both communication and environmental improvement for business-to-business and business-to-consumer analyses (De Camillis et al. 2012).
The ENVIFOOD protocol includes a list of relevant impact categories for the environmental assessment of food and drink products and is expected to have product footprint category rules (PFCR) more detailed than the PCR in the EPD® scheme. Ideally, all relevant life cycle phases should be considered in the system boundary (i.e. the cradle-to-grave approach) and primary and secondary data should be compliant with ILCD Data Network entry level requirements (European Commission, 2010). Special attention in the system boundaries definition is given to the use phase and waste management.
Fresh fruit, belonging to group 1 in the ENVIFOOD protocol, is expected to be studied throughout the full life cycle, including the use phase, if relevant to the PCR. Nevertheless, no specific guidance on how to take

the whole lifetime of orchard systems into account is given. Furthermore, according to the protocol, the impact categories relevant for agriculture and water consumption shall be reported separately.

4. Main challenges and recommendations

4.1 A standard orchard model

The three suggested options for estimating yields (using pre-set estimations, calculating an average or setting a timeframe of validity – see chapter 3.1), do not consider the fact that major diseases or dramatic adverse climate conditions usually affect an entire production area at the same time, influencing the yield factor of the whole region (Sansavini et al., 2012). Furthermore recent research on olive orchards in Southern Italy (Notarnicola et al., 2013) showed that, at the regional level, statistically significant differences may occur in orchard management practices and in farm performance. As a consequence, using a local average for the yield factor could be a good solution to include the variability in orchard inflows/outflows in small districts, but not the variability at the regional level or on the time scale.
A possible way to avoid this problem is to use the annual average of orchard inflows and outflows collected over a period of a certain number of years. Pirilli et al. (2012) suggested that three years could be sufficient but, because of the alternation in production (biennial bearing) in most of the perennial crops in Europe, an even number of years should be adopted. A time interval of four years may be considered as a minimum requirement for data, but the best period of data collection should be based on a crop-specific literature review. Indirect field data may also be used to cover missing years of sampling. For instance, in some countries farmers are asked by the regional authority to keep field logbooks in which they record the main inflows and outflows of their orchards. These data can be used to make an historical weighting of the yearly yield factor.
Furthermore, as an EPD generally stands for three years, continued collection of measured output data for the whole duration of the EPD is suggested. Further updating of the declaration (if requested) may have historical references for a better balanced yield factor.

Even when full sets of field and historical data can be collected, modelling an orchard system with LCA tools may require some recommendations. To this end, we organised the data reported in previous studies in GaBI 4.0 (PE International). In order to avoid calculation errors, six subsystems (hereafter called plans according to operative terminology) were created and connected as follows (Figure 2):

Plan 1: Nursery. All processes and input materials used in the nursery stage can be accounted for using grafted plants to be planted in the orchard as reference flow; indeed, this process represents the connection from the nursery plan to the following parts of the orchard system.
Plan 2: Establishment. In this plan all the processes that occur in the preparation of one hectare of orchard have to be included. The grafted plants are connected from the previous plan through the input of plants per hectare. Plan 2 has to lead to one hectare of ready-to-produce orchard for connecting to the following plan.
Plan 3: Low production years (first part). The plan must include one sub-plan for each year of low production. Including one process for each year would correctly balance the weight of other processes that occur just once in the whole lifetime of the orchard (such as establishment). Each of these sub-plans has to be connected through the reference flow of one hectare of orchard and has to include an open output with the mass of fruit produced for that year. Each sub-plan considers the specific inflows and outflows of the reference year, i.e. the specific farming inputs and the fruit yield. Data for those years may be obtained from field workbooks or may be modelled considering the fruit species and all the agricultural factors (see section 2.3).
Plan 4: Full production years. This plan is connected to the previous one through the reference flow of orchard hectares. This plan must include one sub-plan for each year of full production, which includes the specific inflows and outflows of the reference year, i.e. the specific farming inputs and the fruit yield. Inflows and outflows should be obtained through historical data or can be considered the average of data directly acquired from at least three full production years for all years.

In this case too, each sub-plan has to be connected through the reference flow of orchard hectares, leaving the output of orchard hectares of the last year free to be connected to the following plan. In each year, the specific sub-plan for the output of fruit produced has to be left open.
Plan 5: Low production years (second part). This plan follows the same rules as plan 4 according to the inflows and outflows of the second tail of the model describing senescence of the orchard. Specific data for these years are very rare, but information may be obtained directly from the farm managers. It is not uncommon for the orchard to be removed from production at the first signs of lower production; in this case the low production stage can be avoided and plan 4 may be directly connected to plan 6.
Plan 6: Dismantling. This plan follows the same rules as the establishment plan (2), with the exception of opening an input of orchard hectares in the first process to be connected to the previous plan and closing the output of orchard hectares in the last process because no further connections are required.
Once the six plans are completed and connected, one last process has to be added. This is a fictitious process called “fruit collecting” (Figure 2), which is needed to connect the fruit outflows from the three production plans (3–5) to a single output of fruit mass that can be fixed as the functional unit that best fits the case study (e.g. 1000 kg of fruit in Figure 2). By applying this fictitious process, all the inflows are automatically scaled to the weight of material harvested in each stage. For example, in the case study reported in Figure 2, for the functional unit of 1000 kg of fruit, impacts of the full production years are related to 96.767 kg of output from plan 3 plus 806.47 kg of output from plan 4 and 96.767 kg of output from plan 5. Stages that occur just once in the whole life cycle of the orchard are automatically scaled. In the case study, impacts of installation and dismantling are related to inflows and outflows of 13.967 m^2 of orchard, which virtually represents the production area needed for the functional unit, weighted for the whole lifetime of the orchard. The same process occurs for the nursery, which is connected with the number of grafted plants installed in the “weighted” orchard area, thus depending on orchard density.
We have tested this model several times in order to avoid double accounting or over- and under-estimations of each production stage, but other ways of modelling the whole life cycle of the orchard might be possible.

→ **Figure 3** Orchard modelling of the orchard in GaBI 4.0, PE International.

4.2 Setting LCA parameters for application in fruit production systems

Despite the general standardisation of phases in orchard management, the high variability in farming practices and fruit products leads to different ways of applying LCA in such systems (Bessou et al., 2013). Nevertheless, a standardised model for applying environmental assessment methods to fruit production is useful as a point of departure for more elaborate applications. Otherwise, results may be impossible to compare and risk remaining isolated to the case study. Being able to compare the results from different studies would also allow sustainability thresholds to be identified, as suggested by several authors (e.g. van der Werf and Petit, 2002).
Suggestions for standardisation of assessment method applications in fruit production according to the aim of the study are given in Table 3.

→ **Table 3** Summary of recommendations for LCA properties according to the most highlighted aims in papers considered in the review.

Moreover, considering that inclusion of the whole lifetime of the orchard within the system boundaries is needed, impacts from the nursery phase, orchard establishment and destruction should also be assessed. As orchards are not a single-year production system, the application of an environmental indicator to just the full production year will probably underestimate the real ecological impact by a variable percentage (see section 2.4)
As concluded in other reviews (Petti et al., 2010; Bessou et al., 2013), one of the most frequent problems in environmental assessment of orchards is the difficulty in finding specific data and characterisation factors for pesticides and fertilisers. The fate and effects of chemicals in a particular orchard are very different depending on the pedo-climatic conditions in that orchard. Therefore, it is necessary to conduct the analysis using a predictive mathematical method which can either be used in multi-attributive approaches

to complement LCIA results, such as SYNOPS (Strassemeyer and Gutsche, 2010; Gutsche and Rossberg, 1997), or to model pesticide dispersion so as to be directly integrated into LCIA results, such as PestLCI (Birkved and Hauschild, 2006; Dijkman et al., 2012). In this way, the orchard is considered part of the technosphere. An alternative method is to consider the orchard as part of the environment or natural system and assume that emissions arise as soon as the pesticides are sprayed, and then model their fate using characterisation factors. These approaches lead to different results in the assessment, with potentially dramatic effects in comparisons between studies. Similar considerations can be made when evaluating the impacts of fertilisation. In this regard two approaches are usually applied, use of a detailed orchard model or use of a nutrient balance in which impacts of distribution are related to the effects of surplus nutrients on the environment (Milà I Canals et al., 2006). The latter approach requires specific agronomic investigations about the nutrient demands of the plants and the nutrient content in the soil of the orchard.

Furthermore, the use of different functional units may result in deviating results. The present review of the literature shows that a simple mass-based functional unit is not always able to represent the full complexity of the environmental impacts of orchard systems. Thus, using combined functional units or other functional units may be necessary. For example, a land use-based functional unit can be used together with a mass-based functional unit in order to present a more complete picture and avoid resource use efficiency overvaluation and dislocation of environmental impacts.

As a general remark, when a mass-based functional unit is chosen, the quantity of edible content within the unit should always be indicated. This parameter is absolutely necessary to scale environmental impacts exclusively to the quantity actually consumed (Basset-Mens et al., 2010) for diet studies and product comparisons.

5. Conclusions

This review was based on Peer Reviewed studies of LCA application to fruit production systems all over the world. Although the general common aim of the papers was evaluation of the environmental performance of specific fruit production systems, several different aims were funded across these studies as well a significant heterogeneity in terms of methodological choices.

One of the most crucial aspects in the assessment is that most of the reviewed LCA studies assess perennial systems in the same way as annual crops, and therefore considered only a single productive year in the time boundaries of the system. This problem reflects in a low quality of the orchard model and, possibly, in misestimating the real environmental impact potentials of the production system. Therefore, a general orchard model was developed to include the whole lifetime of the system and practical recommendations are proposed in the paper. The described orchard model should be helpful in initiatives to achieve international harmonization of methods such as the Envifood protocol.

Further studies should focus on:

(I) inclusion of the multi-functionality of orchard systems in the environmental assessment, in particular in relation to the fact that orchards may provide several functions other than fruit, like preserving genetic heritage (Donno et al., 2012) and traditional landscapes (Biasi et al., 2010). Furthermore, trees are often grown in association with other horticultural crops, especially in tropical areas, and the use of specific allocation methods or system expansion approaches should be discussed and validated.

(II) modelling the role of orchards as sinks for CO_2 sequestration. Indeed, orchards, if properly managed, may have high potential for absorption and net storage of CO_2 (Sofo et al., 2005) that might significantly affect results in the Global Warming Potential category (Bosco et al., 2013). A discussion about how to account for carbon sequestration and temporary storage in LCA has recently been presented by Brandão et al. (2013) but specific models for orchard systems were not included.

(III) consolidating results from harmonization initiatives. As highlighted in section 4, different initiatives have suggested alternative settings for LCA applications in fruit production systems. In particular, it could be interesting to have case studies validating and comparing results using recommendations from EPD® either from the EnviFood protocol or other references.

References

ADEME, 2010. La méthode Bilan Carbone®. Agence de L'Environment et de la Maitrise de l'Energie. Available from: www2.ademe.fr

Basset-Mens C., Benoist A., Bessou C., Tran T., Perret S., Vayssieres J., Wassenaar T., 2010. Is LCA-based eco-labeling reasonable? The issue of tropical food products. 7th International Conference on Life Cycle Assessment in the Agri-Food Sector, Bari, Italy, 1:461-466.

Beccali, M., Cellura, M., Iudicello, M., Mistretta, M., 2009. Resource consumption and environmental impacts of the agrofood sector: life cycle assessment of italian citrus-based products. Environmental management. Springer New York. 43, 707-24.

Beccali, M., Cellura, M., Iudicello, M., Mistretta, M., 2010. Life cycle assessment of Italian citrus-based products. Sensitivity analysis and improvement scenarios. Journal of environmental management. 91, 1415-28.

Berners-Lee, M., Hoolohan, C., Cammack, H., Hewitt, C.N., 2012. The relative greenhouse gas impacts of realistic dietary choices. Energy Policy. 43, 184-190.

Bessou C., Basset-Mens C., Tran T., Benoist A., 2013. LCA applied to perennial cropping systems: a review focused on the farm stage. The International Journal of Life Cycle Assessment, 18:340-361.

Biasi R., Botti F., Barbera G., Cullotta S., 2010. The Role of Mediterranean Fruit Tree Orchards and Vineyards in Maintaining the Traditional Agricultural Landscape. ISHS Acta Horticulturae 940:79-88.

Birkved, M., Hauschild, M.Z., 2006. PestLCI—A model for estimating field emissions of pesticides in agricultural LCA. Ecological Modelling 198:433–451.

Blanke, M., Burdick, B., 2005. Food (miles) for Thought - Energy Balance for Locally-grown versus Imported Apple Fruit (3 pp). Environmental Science and Pollution Research - International. Springer Berlin / Heidelberg. 12, 125-127.

Bosco S., Di Bene C., Galli M., Remorini D., Massai R., Bonari E., 2013 Soil organic matter accounting in the carbon footprint analysis of the wine chain. International Journal of LCA. Int J Life Cycle Assess 18:973 – 989.

Brandão M., Levasseur A., Kirschbaum M.U.F., Weidema B.P., Cowie A.L., Jørgensen S.V., Hauschild M.Z., Pennington D.W., Chomkhamsri K., 2013. Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. The International Journal of Life Cycle Assessment, 18:230-240.

BSI, 2011. PAS 2050 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Ed., London, UK.

Carbon Trust, 2007. Carbon footprint measurement methodology. The Carbon Trust Ed., London, UK.

Carlsson-Kanyama, A., Ekström, M.P., Shanahan, H., 2003. Food and life cycle energy inputs: consequences of diet and ways to increase efficiency. Ecological Economics. 44, 293-307.

Cerutti, A.K., Bagliani, M., Beccaro, G.L., Peano, C., Bounous, G., 2010. Comparison of LCA and EFA for the environmental account of fruit production systems: a case study in Northern Italy. Notarnicola, B., Settanni, E., Tassielli, G., Giungato, P. (Eds.), Proceedings of LCA food 2010. Bari, pp. 99-104.

Cerutti, A.K., Galizia, D., Bruun, S., Mellano, G.M., Beccaro, G.L., Bounous, G., 2011. Assessing environmental sustainability of different apple supply chains in northern italy, in: Finkbeiner, M. (Ed.), Towards Life Cycle Sustainability Management. Springer Netherlands, Dordrecht, pp. 341-348.

Cerutti, A.K., Bruun, S., Donno, D., Beccaro, G.L., Bounous, G., 2013. Environmental sustainability of traditional foods: the case of ancient apple cultivars in Northern Italy. Journal of Cleaner Production, 52:245–252.

Clasadonte, M.T., Matarazzo, A., Ingrao, C., 2010a. Life Cycle assessment of Sicilian peach sector. Notarnicola, B., Settanni, E., Tassielli, G., Giungato, P. (Eds.), Proceedings of LCA food 2010. Bari, pp. 295-300.

Clasadonte, M.T., Lo Giudice, A., Ingrao, C., 2010b. Life Cycle Assessment of the Sicilian citrus fruit field. Notarnicola, B., Settanni, E., Tassielli, G., Giungato, P. (Eds.), Proceedings of LCA food 2010. Bari, pp. 301-306.

Coltro, L., Mourad, A.L., Kletecke, R.M., Mendonça, T.A., Germer, S.P.M., 2009. Assessing the environmental profile of orange production in Brazil. The International Journal of Life Cycle Assessment. Springer Berlin / Heidelberg. 14, 656-664.

Cudjoe Adebah, E., Langeveld, C., Kermah, M., 2010. Environmental impact of organic pineapple production in Ghana: a comparison of two farms using Life Cycle Assessment (LCA) approach.

De Camillis C., Bligny J.C., Pennington D., Pályi B., 2012. Outcomes of the second workshop of the Food Sustainable Consumption and Production Round Table Working Group 1: deriving scientifically sound rules for a sector-specific environmental assessment methodology. International Journal of Life Cycle Assessment, 17:511 – 515.

Del Borghi, A., 2013. LCA and communication: Environmental Product Declaration. International Journal of Life Cycle Assessment, 18:293-295.

Dijkman, T. J., Birkved, M., Hauschild, M.Z., 2012. PestLCI 2.0: a second generation model for estimating emissions of pesticides from arable land in LCA. International Journal of Life Cycle Assessment, 17:973–986.

Donno, D. , Beccaro, G.L., Mellano, M.G., Torello Marinoni, D., Cerutti, A.K., Canterino, S., Bounous, G., 2012. Application of sensory, nutraceutical and genetic techniques to create a quality profile of ancient apple cultivars Journal of Food Quality, 35(3):169-181.

European Commission, 2010. The International Reference Life Cycle Data System (ILCD) Data Network — compliance rules and entry-level requirements. European Commission, DG-JRC.

European Commission, 2012. Environmental assessment of Food and Drink Protocol. Draft Version 0.1 For Pilot Testing November 2012. European Food Sustainable Consumption and Production Roundtable.

European Commission, 2013. Product Environmental Footprint (PEF) Guide. European Commission, DG-JRC Ref. Ares(2012)873782 - 17/07/2012.

Gutsche V., Rossberg D., 1997. SYNOPS 1.1: a model to assess and to compare the environmental risk potential of active ingredients in plant products. Agriculture, Ecosystem and Environment, 64:181–188.

Hauschild MZ (2000) Estimating pesticide emissions for LCA of agricultural products. In: Weidema BP, Meeusen MJG (eds) Agricultural data for life cycle assessments, vol. 2. LCANet Food, The Hague, The Netherlands, pp 64–79.

Hayashi, K., 2013. Practical recommendations for supporting agricultural decisions through life cycle assessment based on two alternative views of crop production: the example of organic conversion. The International Journal of Life Cycle Assessment, 18:331-339.

Ingram, D.L., 2012. Life cycle assessment of a field-grown red maple tree to estimate its carbon footprint components. International Journal of Life Cycle Assessment, 17:453-462.

Ingwersen, W., 2010. Product category range of environmental performance for EPDs: example of Costa Rican pineapple. Notarnicola, B., Settanni, E., Tassielli, G., Giungato, P. (Eds.), Proceedings of LCA food 2010. Bari, pp. 337-341.

Ingwersen, W., Stevenson, M.J., 2012. Can we compare the environmental performance of this product to that one? An update on the development of product category rules and future challenges toward alignment. Journal of Cleaner Production, 24:102-108.

ISO, 2013. ISO/DIS 14046 Environmental management -- Water footprint -- Principles, requirements and guidelines.

ISO, 2013. ISO/TS 14067:2013 Greenhouse gases -- Carbon footprint of products -- Requirements and guidelines for quantification and communication.

Knudsen, M.T., Fonseca de Almeida, G., Langer, V., Santiago de Abreu, L., Halberg, N., 2011. Environmental assessment of organic juice imported to Denmark: a case study on oranges (Citrus sinensis) from Brazil. Organic Agriculture. Springer Netherlands. 1, 167-185.

Liu, Y., Langer, V., Høgh-Jensen, H., Egelyng, H., 2010. Life Cycle Assessment of fossil energy use and greenhouse gas emissions in Chinese pear production. Journal of Cleaner Production. 18, 1423-1430.

McLaren, S.J., Hume, A., Mitraratne, N., 2010. Carbon management for the primary agricultural sector in New Zealand: case studies for the pipfruit and kiwifruit industries. Notarnicola, B., Settanni, E., Tassielli, G., Giungato, P. (Eds.), Proceedings of LCA food 2010, pp. 293-298.

Milà I Canals, L., Burnip, G.M., Cowell, S.J., 2006. Evaluation of the environmental impacts of apple production using Life Cycle Assessment (LCA): Case study in New Zealand. Agriculture, Ecosystems & Environment. 114, 226-238.

Milà i Canals, L., Cowell, S.J., Sim, S., Basson, L., 2007. Comparing domestic versus imported apples: A focus on energy use. Environmental Science and Pollution Research - International. Springer Berlin / Heidelberg. 14, 338-344.

Mouron, P., Scholz, R.W., Nemecek, T., Weber, O., 2006 a. Life cycle management on Swiss fruit farms: Relating environmental and income indicators for fruit growing. Ecological Economics 58, 561-578.

Mouron, P., Nemecek, T., Scholz, R.W., Weber, O., 2006 b. Management influence on environmental impacts in an apple production system on Swiss fruit farms: Combining life cycle assessment with statistical risk assessment. Agriculture, Ecosystems & Environment. 114, 311-322.

Mouron, P., Heijne, B., Naef, A., Strassemeyer, J., Hayer, F., Avilla, J., Alaphilippe, A., Höhn, H., Hernandez, J., Gaillard, G., Mack, G., Solé, J., Sauphanor, B., Samietz, J., Patocchi, A., Bravin, E., Lavigne, C., Bohanec, M., Aubert, U., Franz Bigler, 2012. Sustainability assessment of crop protection systems: SustainOS methodology and its application for apple orchards. Agricultural Systems 113 (2012) 1-15.

Nemecek, T., Huguenin-Elie, O., Dubois, D., Gaillard, G., Schaller, B., Chervet, A., 2011. Life cycle assessment of Swiss farming systems: II. Extensive and intensive production. Agricultural Systems 104:233–245.

Notarnicola B., Tassielli G., Renzulli P.A., 2012a. Modeling the agri-food industry with Life Cycle Assessment. In: Curran, M. (Ed.) Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products, Wiley, Scrivener Publishing, Salem, MA.

Notarnicola, B., Hayashi K., Curranc M.A., Huisinghd D., 2012b. Progress in working towards a more sustainable agri-food industry. Journal of Cleaner Production, 28:1–8.

Notarnicola B., Tassielli G., Renzulli P.A., 2013. La variabilità dei dati nella LCA della produzione olivicola. Proceeeding of theVII Congress of the Italian LCA Network. pp. 29-35. ISBN 978-88-8286-292-3.

Peacock N., De Camillis C., Pennington D., Aichinger H., Parenti A., Rennaud J., Raggi A., Brentrup F., Sára B., Schenker U., Unger N., Ziegler F., 2011. Towards a harmonised framework methodology for the environmental assessment of food and drink products. The International Journal of Life Cycle Assessment, 16:189-197.

Petti, L., Ardente, F., Bosco, S., De Camillis, C., Masotti, P., Pattara, C., Raggi, A., Tassielli, G., 2010. State of the art of Life Cycle Assessment in the wine industry. In Notarnicola B., Settanni E., Tassielli G., Giungato P. (Eds.), Proceedings of LCA food 2010. Bari, vol. 1, pp. 493-498.

Pirilli, M., Falcone, G., Strano, A., 2012. La formazione dell'inventario per l'LCA nei confronti fra processi produttivi agricoli nella clementinicoltura in Calabria. Proceedings of the VI Congress of the Italian LCA Network, Bari, 7-8 June, 2012.

Russo, G., Scaraascia Mugnozza G., 2005. LCA methodology applied to various typology of greenhouses. Acta Horticulturae, 691:837-843.

Sanjuan, N., Ubeda, L., Clemente, G., Mulet, A., Girona, F., 2005. LCA of integrated orange production in the Comunidad Valenciana (Spain). International Journal of Agricultural Resources, Governance and Ecology 4 (2), 163-177.

Sansavini, S., Costa, G., Gucci, R., Inglese, P., Ramina, A., Xiloyannis, C., (Eds) 2012. Arboricoltura generale. Pàtron Editore Bologna, Italy.

Sim, S., Barry, M., Clift, R., Cowell, S.J., 2007. The relative importance of transport in determining an appropriate sustainability strategy for food sourcing. The International Journal of Life Cycle Assessment. Springer Berlin / Heidelberg. 12, 422-431.

Sofo A, Nuzzo V., Palese A.M., Xiloyannis C., Celano G., Zukowskyj P., Dichio B., 2005. Net CO2 storage in mediterranean olive and peach orchards, Scientia Horticulturae, 107:17–24.

Strassemeyer, J., Gutsche, V., 2010. The Approach of the German Pesticide Risk Indicator SYNOPS in the Frame of the National Action Plan on the Sustainable Use of Pesticides, OECD Workshop on Agri-Environmental Indicators, Leysin, Switzerland. <http://www.oecd.org/dataoecd/32/16/GGTSPU-styx2.bba.de-11619-4690407-DAT/44806454.pdf>.

van der Werf, H.M.G., Petit, J., 2002. Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. Agric. Ecosyst. Environ. 93, 131–145.

van der Werf, H.M.G., Tzilivakis, J., Lewis, K., Basset-Mens, C., 2007. Environmental impacts of farm scenarios according to five assessment methods. Agriculture, Ecosystems and Environment, 118:327–338.

Wackernagel, M., Rees, W., 1997. Perceptual and structural barriers to investing in natural capital: economics from an ecological footprint perspective. Ecological Economics 20(1):3-24.

Wallén, A., Brandt, N., Wennersten, R., 2004. Does the Swedish consumer's choice of food influence greenhouse gas emissions? Environmental Science & Policy 7, 525-535.

Williams, A., Pell, E., Webb, J., Moorhouse, E., Audsley, E., 2008. Strawberry and tomato production for the UK compared between the UK and Spain. Proceedings of the 6th International Conference on LCA in the Agri-Food Sector, pp. 254-262.

WBCSD/WRI, 2009. The greenhouse gas protocol. A corporate account-ing and reporting standard. World Resources Institute-World Business Council for Sustainable Development, Washington, DC, USA.

Yusoff, S., Hansen, S.B., 2007. Feasibility study of performing an life cycle assessment on crude palm oil production in Malaysia. International Journal of Life Cycle Assessment 12, 50-58.

Zackrisson, M., Rocha, C., Christiansen, K., Janehammar, A., 2008. Stepwise environmental product declaration: ten SME case studies. Journal of Cleaner Production 16:1872-1886.

Figures and Tables

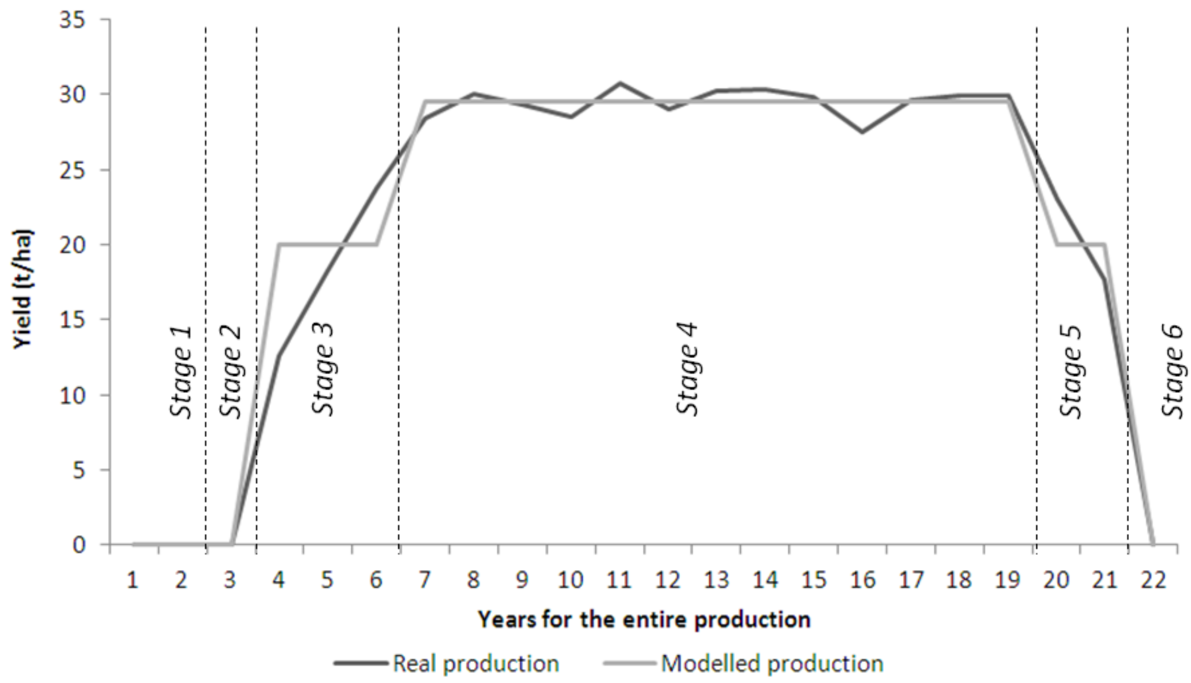

Figure 1: Graphic representation of real and modelled production throughout the entire life of an apple orchard in Cuneo province, northern Italy, divided into six stages of production (modified from Cerutti et al., 2011)

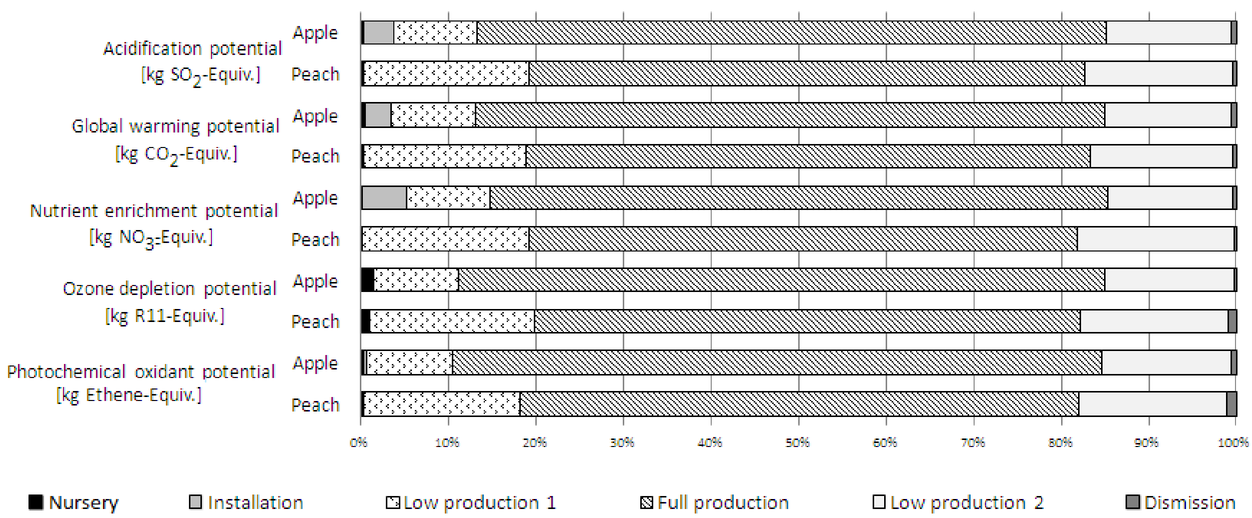

Figure 2. Hotspot analysis of two previous case studies. Modified from Cerutti et al., 2011.

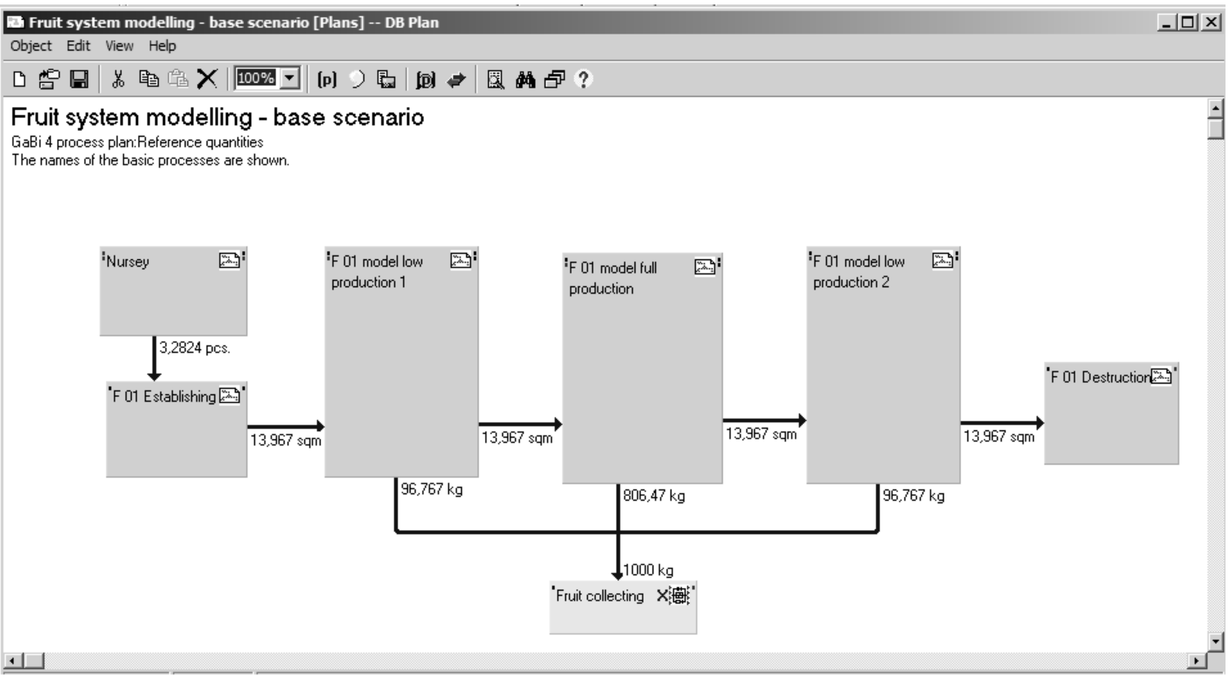

Figure 3. Orchard life cycle modelling in Gabi 4.0.

Table 1. List of all papers from ISI journals and conferences that present applications of LCA in fruit production systems up to January 2013, listed by ascending date of publication. Country category considers the area of the study and not necessarily the location of the research group. Objectives: 1) profile the environmental burden of a fruit product; 2) identify the environmental hotspots in production systems performance; 3) describe management strategies to increase environmental performance; 4) compare the environmental burden of different food products on a common functional unit; 5) compare different farming practices; 6) compare different environmental assessment methods; 7) profile the environmental burden of production in a given area; 8) evaluate the environmental properties of a supply chain; and 9) assess a preliminary study for statistical investigations.

REFERENCE	COUNTRY	PRODUCT	MAIN OBJECTIVES	FUNCTIONAL UNIT	BOUNDARIES	DATASET	ASSESSMENT METHOD
Blanke and Burdick, 2005	Germany, New Zealand	Apple	8	Mass-based (kg)	Cradle-to-market	Literature and other databases	Characterisation factors from literature
Sanjuán et al., 2005	Spain	Orange	1, 2, 7	Mass-based (kg)	Cradle-to-gate	Literature and other databases	CML, WMO, POPC and USES
Milà i Canals et al., 2006	New Zealand	Apple	1, 2, 3	Mass-based (t)	Cradle-to-market	Commercial orchards + validation	EDIP1997
Mouron et al., 2006	Swiss	Apple	1, 2, 3, 7	Land-based (ha); Currency-based ($)	Cradle-to-gate	Commercial orchards	SALCA (2003)
Milà i Canals et al., 2007	UK, New Zealand	Apple	8	Mass-based (kg)	Cradle-to-market	Literature and specific databases	Characterisation factors from literature
Sim et al., 2007	Brazil, Chile, Italy, UK	Apple	8	Mass-based (t, just grade 1)	Cradle-to-retailer	Literature and specific databases	CML 2 Baseline 2000
Williams et al., 2008	UK, Spain	Strawberry	8	Mass-based (t at distribution)	Cradle-to-market	Literature and specific databases	Characterisation factors from literature
Beccali et al., 2009	Italy	Citrus-based products	1	Mass-based (kg of juices and oil)	Cradle-to-market	Primary data from field and secondary from literature	IPCC 2001 GWP100; CML 2 Baseline 2000
Coltro et al., 2009	Brazil	Orange	1, 7	Mass-based (t)	Cradle-to-gate	Commercial orchards	Characterisation factors from literature
Beccali et al., 2010	Italy	Citrus-based products	3	Mass-based (kg of juices and oil)	Cradle-to-market	Primary data from field and secondary from literature	IPCC 2001 GWP100; CML 2 Baseline 2000
Cerutti et al., 2010	Italy	Peach	1, 2, 6	Mass-based (kg)	Cradle-to-gate	Commercial orchards + validation	Eco-Indicator 99
Cudjoe et al., 2010	Ghana	Pineapple	2, 3	Mass-based (kg)	Cradle-to-gate	Commercial orchards	Characterisation factors from literature
Ingwersen, 2010	Costa Rica	Pineapple	1, 9	Mass-based (serving portion)	Cradle-to-retailer	Commercial orchards	ecoinvent 2.0
Liu et al., 2010	China	Pear	2, 8	Mass-based (t)	Cradle-to-market	Commercial orchards	IPCC 2007
Clasadonte et al., 2010a	Italy	Peach	4	Mass-based (kg)	Cradle-to-gate	Commercial orchards	Impact 2002+
Clasadonte et al., 2010b	Italy	Orange	1, 3	Mass-based (kg)	Cradle-to-gate	Commercial orchard	Impact 2002+
McLaren et al., 2010	New Zealand	Apple, Kiwifruit	1, 3, 6	Mass-based (kg)	Cradle-to-use	Commercial orchards	PAS 2050
Cerutti et al., 2011	Italy	Apple	8	Mass-based (kg)	Cradle-to-market	Retailer and associated orchards	EDIP 1997
Knudsen et al., 2011	Brazil	Orange	5, 8	Mass-based (l of juice); Mass-based (t of fruit)	Cradle-to-market Cradle-to-gate	Commercial orchards and statistics	EDIP 1997 + IPCC 2007 (GHG); IMPACT2002+ (energy)

Table 2. Description of all the PCRs (and relative EPDs) which consider fruit products, both fresh and processed, registered in the EPD® system.

PCR Name	PCP product code	Moderator	Status	Related EPD	EPD code
Fruits and nuts	Group 013: Fruits and nuts, and the following classes Class 0131: Tropical and subtropical fruits Class 0132: Citrus fruits Class 0133: Grapes Class 0134: Berries Class 0135: Pome fruits and stone fruits Class 0136: Fruit seeds Class 0137: Nuts Class 0139: Other fruits, n.e.c.	George Michalopoulos RodaxAgro LTD	Completed	Apples from Trentino-Alto Adige	S-P-00369
Kiwifruit	Class 01342: Kiwifruit	John Andrews Landcare Research, New Zealand	Completed	Kiwifruit produced by Zeus Kiwi SA in Greece	S-P-00310
Fruit juices	Class 2143:Fruit juices	Massimo Marino Life Cycle Engineering Italy	Completed	--	--
Jams, fruit jellies and marmalades	Class 21494: Jams, fruit jellies, marmalades, fruit or nut purree and fruit or nut paste	Assunta Filareto Life Cycle Engineering	Completed	--	--
Other prepared and preserved fruit and nuts	Class 2149: Other prepared and preserved fruit and nuts	Adriana Del Borghi Dpt Chem & Process Engineering, University of Genoa	Open consultation	--	--
Table olives	Class 0145: Olives	George Michalopoulos RodaxAgro LTD	Under review	--	--

Table 3. Summary of recommendations for LCA properties according to the most highlighted aims in papers considered in the review.

	Profile environmental burdens of a product	**Profile environmental burdens of a supply-chain**	**Comparing different products or farming practices**	**Profile environmental burdens of a production area**
Data quality requirement	Field data collected in even number of years (at least 4); literature data should be avoided completely	Field data collected in even number of years (at least 4); literature data can be used but consistence has to be checked	Field data collected in even number of years (at least 4); literature data can be used but consistency has to be checked	Field data collected in even number of years (at least 4); literature data should be avoided completely
Number of production sites to be investigated	At least 3 orchards per set of agronomic parameters*	At least 3 orchards per set of agronomic parameters*	At least 3 orchards per set of agronomic parameters*	At least 3 orchards per set of agronomic parameters* choosing sites most distant from each other
Suggested weighing method(s)	Impacts of production sites weighted on farm yield	Impacts of production sites weighted on farm yield	Two sets of results: one based on impacts of production sites weighted on farm yield and on farm dimension	Production sites weighted on farm dimensions
System boundaries	Cradle-to-gate	Cradle-to-consumption	Cradle-to-gate	Cradle-to-gate

Functional Unit(s)	1 ton of final product,	1 portion of the edible part of the fruit	1 ton of final product, 1 ha of orchard, 1 currency unit earned	1 ton of final product, 1 ha of orchard,
Suggested further use	Reference study for environmental product declarations or databases	Reference study for assessing environmental burden of diets	Reference study for greener production design	Reference study for environmental product declarations or databases

* A set of agronomic parameters encompassing all aspects specific to the plantation, such as production protocol (conventional, integrated, organic), cultivar planted and soil type.